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An Ultra-Low Phase Noise Multi-Frequency Source

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Design and construction of a prototype X-band pulse-Doppler radar having 90 dB of dynamic range (after pulse integration and into a 1 MHz band) calls for a ultra-low phase noise multi-frequency source. The generated frequencies for local oscillators (LOs), waveform generation, and data acquisition typically cover the spectrum from HF to X-band and must be coherent. However, using a separate synthesizer for each required frequency would be both costly and cumbersome. This report describes an inexpensive, lightweight, compact, low phase-noise source that coherently generates, within a single chassis, all the frequencies required of a high-performance radar system. Moreover, the multi-frequency source has a tunable output providing frequencies from UHF to K-band. This report emphasizes "how to build" rather than detailed design theory. However, the report does present phase-noise test results and suggested improvements for a second design iteration. The multi-frequency source is versatile and can also be used for bench testing RF and microwave components.

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CONTENTS

FIGURES

TABLES

AN ULTRA-LOW PHASE NOISE MULTI-FREQUENCY SOURCE

1. INTRODUCTION

Design and construction of a prototype X-band pulse-Doppler radar having 90 dB of dynamic range (after pulse integration and into a 1 MHz bandwidth) calls for an ultra-low phase noise multi-frequency source. The generated frequencies for local oscillators (LOs), waveform generation, and data acquisition typically cover the spectrum from HF to X-band and must be coherent. Up and down conversion require two or three LO frequencies. Timing, waveform generation, and data acquisition can require several more frequencies. Building such a radar system just described using separate synthesizers for each frequency would be extremely costly, bulky, heavy, and inconvenient.

This report describes a compact, lightweight, ultra-stable source that coherently generates all of the required LO frequencies of a high-performance X-band radar system. This multi-frequency source, often referred to as "the source" in this document, is shown in Figure 1.

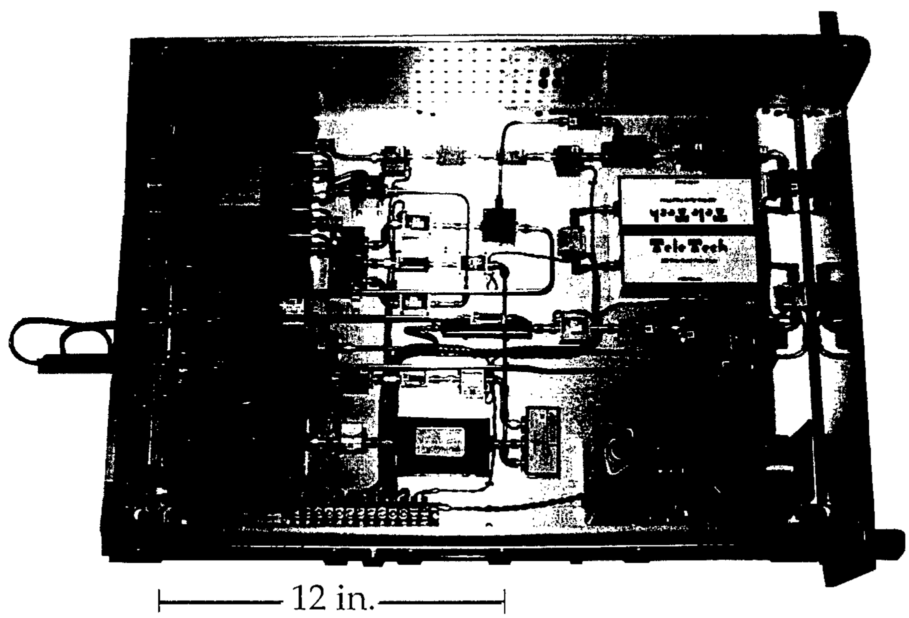

Fig. 1 - The multi-frequency source

The source is compact and fits in a standard 19-inch-rack chassis that is only 5.25 in. tall. The source weighs only 28 lbs. including the power supply. It is economical, costing only $ 19K to build. It is convenient to use because it does not require daisy chaining a reference frequency among several synthesizers to achieve coherency. The only limitation of the source is that it operates at fixed output frequencies and therefore, cannot be arbitrarily and conveniently tuned like a synthesizer. On the other hand, one of the source's outputs is adjustable from 640 to 16,000 MHz at intervals of 640 MHz by simply changing an externally mounted filter (left-side in Figure 1) and an internally mounted output amplifier (one amplifier alone cannot cover the entire operating band).

Manuscript approved September 28, 1998

2. SYSTEM REQUIREMENTS

Compatibility with several recently built systems in the Radar Division of the Naval Research Laboratory dictated many of the system requirements for the source. Table 1 lists both the hardware interface requirements and the phase-noise related goals for the multi-frequency source. The "non-harmonically related spurs entry" in Table 1 refers to discrete frequencies appearing anywhere in the output spectrum including the single sideband (SSB) phase-noise plot. The phase-noise goals were ambitious for a source consisting of predominately commercial off-the-shelf (COTS) components. They were based wherever possible, on the performance of a custom multi-frequency source that was used in an experimental, high-dynamic-range, pulse-Doppler radar system. The 8320, 1430, and 32.5 MHz formed a LO group for testing a receiver with 80 dB of single-tone dynamic range. The 10 MHz, selected for its equivalent sub-picosecond time base jitter, was converted into an ECL sampling clock for a 16-bit analog to digital converter (ADC) with 83 dB signal-to-noise ratio. The 160 and 2.5 MHz were used for clocking a data collection system. The 320 MHz was included as an auxiliary output. All these requirements allow the multi-frequency source to function as the master frequency generator for a high-performance radar system.

Table 1 - System Requirements for the Multi-Frequency Source

Output frequencies	
Variable:	640 - 16,000 MHz in 640 MHz steps (8320 MHz was required)
Fixed:	1430, 640, 320, 160, 32.5, 20, 10, and 2.5 MHz
Output power:	0 to +10 dBm
External phase locking:	not required
Output impedance:	50Ω
Connectors:	SMA - jack
Harmonic levels:	-40 dBc
Non-harmonically related spurs:	-60 dBc
AM noise:	at or below SSB phase noise

SSB phase noise goals (dBc/Hz)						
Offset (Hz)	8320 MHz	1430 MHz	320 MHz	32.5 MHz	20 MHz	10 MHz
10	-66	-80	-76	-88	-115	-108
100	-100	-114	-108	-120	-145	-140
1K	-125	-139	-133	-145	-163	-165
10K	-133	-147	-141	-153	-165	-165
100K	-143	-157	-151	-163	-167	-165
Floor	-148	-162	-156	-168	-168	-165

3. WENZEL ASSEMBLY

The heart of the multi-frequency source is the custom-made Wenzel assembly, which coherently generates 80, 32.5, 20, 10, and 2.5 MHz. The Wenzel assembly is shown in the upper

left corner of Figure 1. Within the Wenzel assembly, the 80 MHz reference is frequency divided five times to generate the 40, 20, 10, 5 and 2.5 MHz. (The 5 and 40 MHz are not available as outputs.) Since 32.5 MHz and 80 MHz are not integer related, a separate 32.5 MHz crystal oscillator was phase-locked to the 80 MHz reference.

The phase-noise performance of the output frequencies, other than 32.5 MHz, is directly related to the 80 MHz reference. This reference is multiplied in frequency, by a circuit external to the Wenzel assembly, in order to generate the required VHF, UHF, and microwave output frequencies. Ideal frequency multiplication increases phase noise according to the following expression [1]:

$$\Delta M = 20 \cdot \log\left(\frac{f_{out}}{f_{in}}\right)$$

Applying this expression to the multiplication of the 80 MHz reference (f_{in}) to yield the 640 MHz output (f_{out}) results in a phase noise increase (ΔM) of 18 dB. Therefore, it was imperative to begin with a reference having the lowest possible phase noise at all offsets. Table 2 lists the specifications, taken directly from the Wenzel catalog, of the 80 MHz reference selected for use in the Wenzel assembly.

Table 2 - 80 MHz Crystal Oscillator Specifications	
Vendor:	Wenzel Associates Inc.
Model number:	Ultra-Low Noise, 80 MHz-SC premium
Aging:	0.3 ppm/year
SSB phase noise:	
Offset (Hz)	(dBc/Hz)
100	-132
1K	-162
10K	-177
20K	-178
Temperature stability:	± 0.7 ppm
Tuning range:	± 4 ppm
Supply voltage:	15 VDC ± 5%
Oven controlled	yes

Table 3 lists the measured phase noise performance of the various output frequencies. Given the test set measurement error of about 1.5 dB, the 80 MHz meets the phase noise specification listed in Table 2.

Table 3 - SSB Phase-Noise for the Wenzel Assembly P/N 500-05125 (dBc/Hz)

(Supplied by the Wenzel Associates Inc.)

Offset (Hz)	80 MHz	32.5 MHz	20 MHz	10 MHz	2.5 MHz
10	-108	-109	-110	-119	-125
100	-137	-136	-143	-150	-157
1K	-166	-160	-162	-167	-169
10K	-176	-173	-166	-169	-170
100K	-177	-174	-167	-169	-170
Floor	-177	-174	-167	-169	-170

4. CIRCUIT DESCRIPTION

The block diagram of the multi-frequency source, shown in Figure 2, consists of two subassemblies: the Wenzel assembly and the microwave generator circuit. As mentioned in Section 3, the 80 MHz output from the Wenzel assembly functions as the reference frequency for the source. The 32.5, 20, 10, and 2.5 MHz frequencies are all brought out on SMA connectors. The 80 MHz is input to a cascade of four frequency-doubling networks in the microwave generator circuit to generate the four intermediate frequencies: 160, 320, 640, and 1280 MHz. Throughout the microwave generator circuit all amplifiers (except A12) and mixers are driven at their respective compression points in order to suppress AM noise.

The amplifier A1 provides gain and isolation from the output filter inside the Wenzel assembly while the frequency doubler FD1 generates 160 MHz. The bandpass filter FL1, centered at 160 MHz, removes the DC and the harmonics generated by FD1. The amplifier A2 provides gain and isolation from filter FL1. The 160 MHz output of amplifier A2 is coupled down by 10 dB at CPL1, further filtered by FL6, power divided by PD2, and brought out on a SMA connector.

The frequency doubler FD2 generates 320 MHz. The bandpass filter FL2, centered at 320 MHz, removes the DC and the harmonics generated by FD2. The 320 MHz is then applied to a surface acoustic wave (SAW) filter network consisting of FL3 and FL4. The primary purpose of the 320 MHz SAW filter FL3 is to improve the noise floor. The frequency-doubling operations at 80 and 160 MHz elevated the noise floor by 12 dB. However, the SAW filter, with its extremely narrow bandwidth of 44 kHz, reduces the out-of-band noise by 12 dB thus restoring the 320 MHz floor to the level at 80 MHz. Reductions in the noise floor greater than this will not improve the phase noise at the output. In addition to noise-floor improvement, both SAW filters suppress spurious signals. Amplifiers A4 and A5 provide 24 dB of gain needed to offset the combined insertion losses of the two SAW filters.

The third frequency doubler FD3 generates 640 MHz, which is filtered by FL7, isolated by A6, coupled down 10 dB by CPL3, and further filtered by FL10. The 640 MHz is then brought out on a SMA connector. The 640 MHz is also power split and applied to a step recovery diode (SRD). The SRD generates synchronous comb-lines equally spaced at 640 MHz. The filter FL11 and the amplifier A12 select and amplify the 8320 MHz line, which is the 13th harmonic of 640 MHz. Any harmonic of the 640 MHz can be selected by simply changing the filter FL11, which is external to the source enclosure. Note that the frequency range of the MMIC amplifier A12 lies within the ninth and eighteenth harmonic of 640 MHz. Outside this range, a different amplifier must be used.

The fourth and final frequency doubler FD4 generates 1280 MHz. The filter FL8 removes the DC and the harmonics generated by FD4. The amplifier A7 provides isolation between the highly reactive source FL8 and the termination-sensitive load MX1. The mixer MX2 uses the 160 MHz from power divider PD2 and the 10 MHz from the Wenzel assembly to generate 150 MHz. The 150 MHz is filtered by FL9 and buffered by A8 to provide a LO for mixer MX1. The mixer MX1 upconverts the 1280 MHz to 1430 MHz. Using FL12, A13, and FL13, the 1430 MHz is filtered, amplified, and filtered again, respectively, and brought out on a SMA connector. A complete parts list for the multi-frequency source is given in Appendix A.

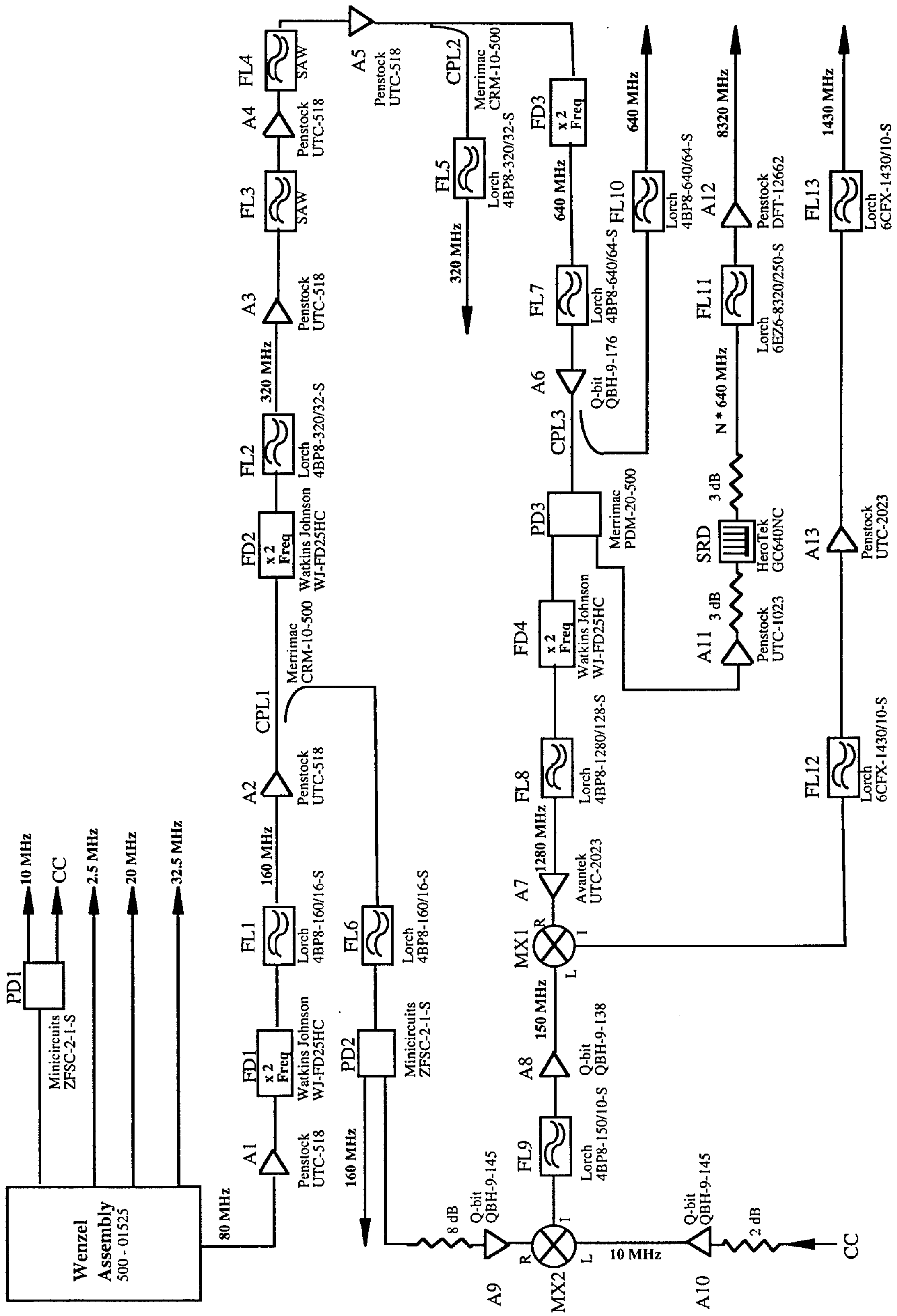

Fig. 2 - Block diagram of the multi-frequency source

5. SAW FILTER

The two identical 320 MHz SAW filters were constructed from a Northrop Grumman Corporation (NGC) design. Each SAW filter consists of the following: SAW resonator, input/output matching networks, heater, and case. The resonator, with specifications listed in Table 4, was based on an existing Sawtek Incorporated device. Tele Tech Incorporated assembled the components into a compact case complete with SMA connectors and a DC power pin for the heater. The SAW filter schematic is shown in Figure 3. The heater, which contains a proportional-integral-differential (PID) controller, keeps the SAW resonator at the turnover temperature. Thus, variations in ambient temperature and drive level will not cause drifts in the center frequency. During the tuning procedure, a tradeoff was made to minimize the return loss (lowest VSWR) over the insertion loss. Figures 4 and 5 show the insertion loss and return loss, respectively, for a completed SAW filter as measured by Tele Tech Incorporated.

Table 4 - SAW Resonator Characteristics

Vendor:	Sawtek Inc.
Part number:	851779
Center frequency:	319.984 - 320.016 MHz
Unloaded Q:	14,500 min
Insertion loss:	5 dB max
Stopband rejection	
309.999 - 319.799 MHz	12 dB min
320.199 - 329.990 MHz	12 dB min
Package:	TO-8

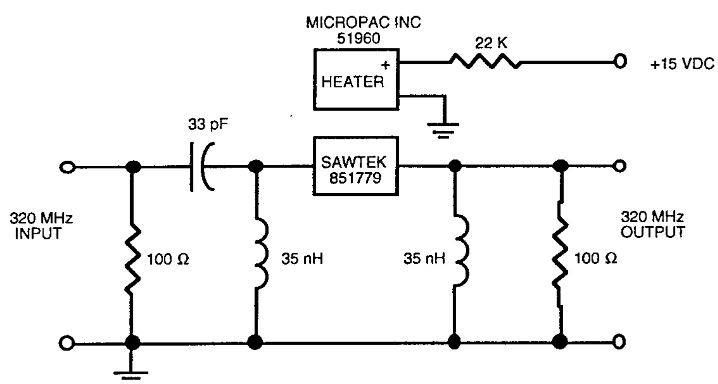

Fig. 3 - SAW filter circuit

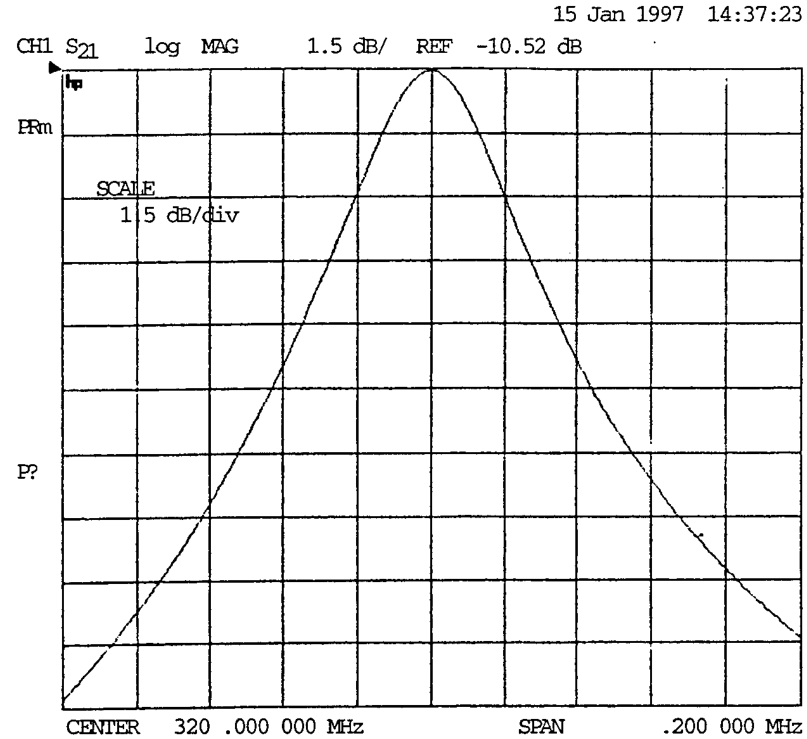

Fig. 4 - Insertion loss for the SAW filter

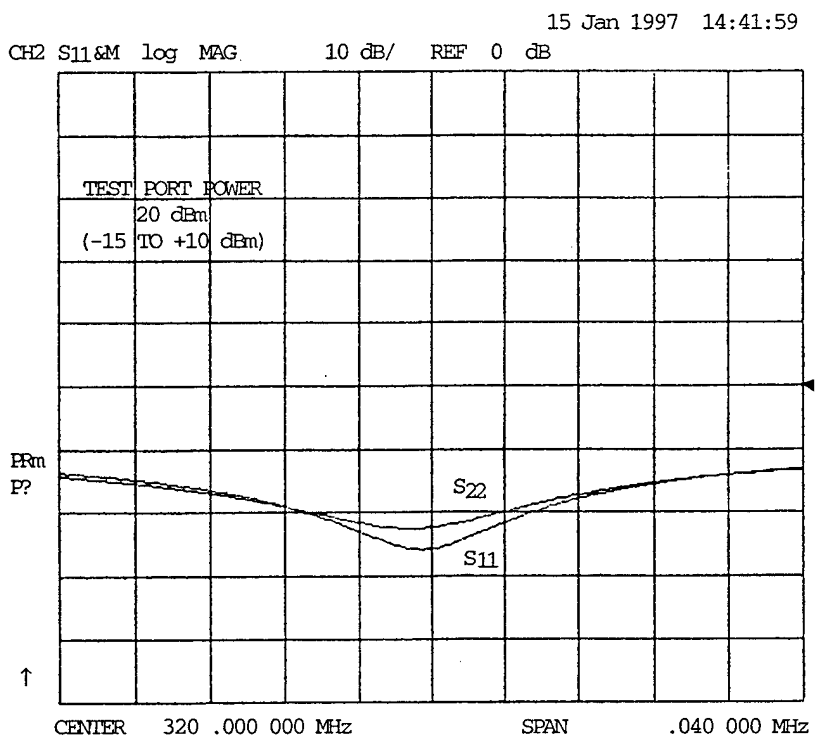

Fig. 5 - Return loss for the SAW filter

6. MEASURED PERFORMANCE

Phase-noise testing of the multi-frequency source was performed at NGC in Linthicum, MD during February 1997. The test set-up, shown in Figure 6, consists of the Hewlett Packard HP 3047 phase-noise test set and a tunable reference source having known phase-noise performance. The tune voltage output of the HP 3047 keeps the reference source locked in frequency and in quadrature with the free running device under test (DUT). Testing of the DUT was limited to the six output frequencies available from the reference source as indicated in Figure 6.

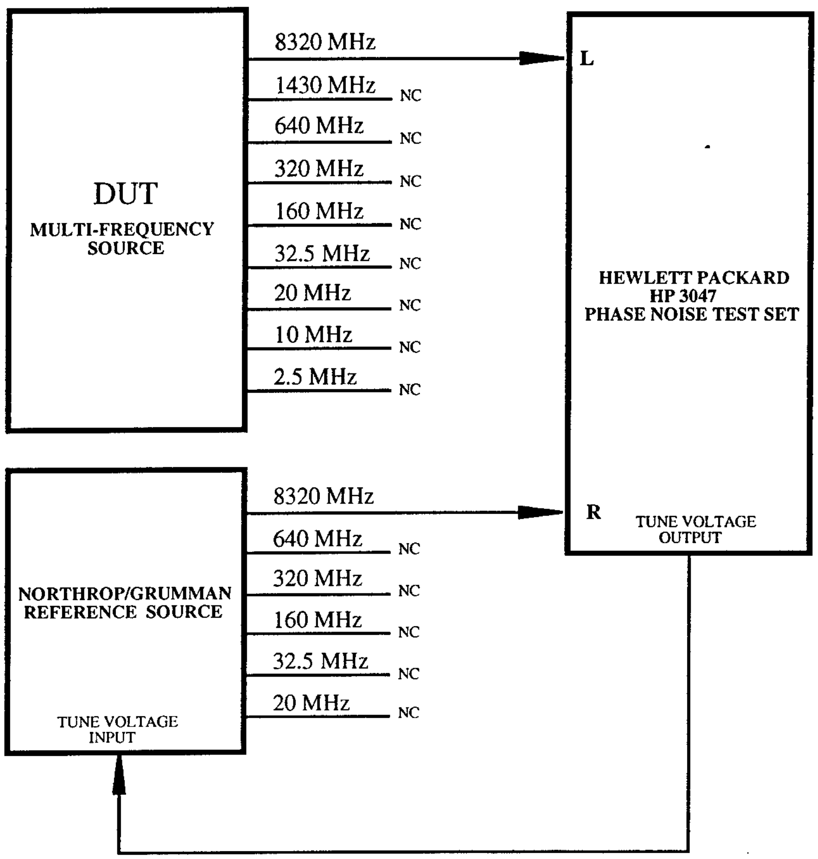

Fig. 6 - Test setup for measuring SSB phase noise at 8320 MHz

The measured phase-noise profiles in Table 5 were taken directly from the plots (the spurs are not indicated). The 10, 32.5 and 320 MHz frequencies met the phase-noise goals given in Table 1. Moreover, the 20 MHz phase-noise goals were also met except for the 10 and 100 Hz offsets. The 8320 MHz, which did not meet the phase noise goals stated in Table 1, still has admirable phase noise performance. Compared to the leading manufacturer's premium synthesizer costing $ 63K, the source has the same phase-noise profile from 100 kHz outward. From 100 Hz to 10 kHz, the source performs better than the premium synthesizer by several dB. From Table 5, only the 320 and 8320 MHz were selected for detailed discussions. The AM noise requirement in Table 1 was not verified.

Table 5 - SSB Phase-Noise Data for the Multi-Frequency Source (dBc/Hz)						
Offset (Hz)	8320 MHz	640 MHz	320 MHz	160 MHz	32.5 MHz	20 MHz
10	-58	-82	-90	-97	-100	-108
100	-92	-114	-121	-130	-135	-143
1K	-120	-143	-147	-155	-164	-162
10K	-131	-154	-160	-164	-171	-165
100K	-142	-166	-174	-164	-171	-167
Floor	-144	-169	-174	-164	-171	-169

Theory predicts the 8320 MHz to have the poorest phase noise of all the measurable output frequencies (see Formula 1). Thus, a phase-noise measurement of the 8320 MHz output is the most revealing indicator of system performance. The plot for the phase noise for the 8320 MHz output, shown in Figure 7, represents the combined phase noise of both sources. The phase noise of the reference source at offsets less than 100 Hz is known to be 10 dB better than in Figure 7. Therefore, below 100 Hz offset, the curve shows the performance of DUT alone. Above 100 Hz, the two sources are equal contributors with the DUT being 3 dB better than the curve in Figure 7. The bump with a peak at 7 kHz is due to the upper band edge of the 320 MHz SAW filter in each source.

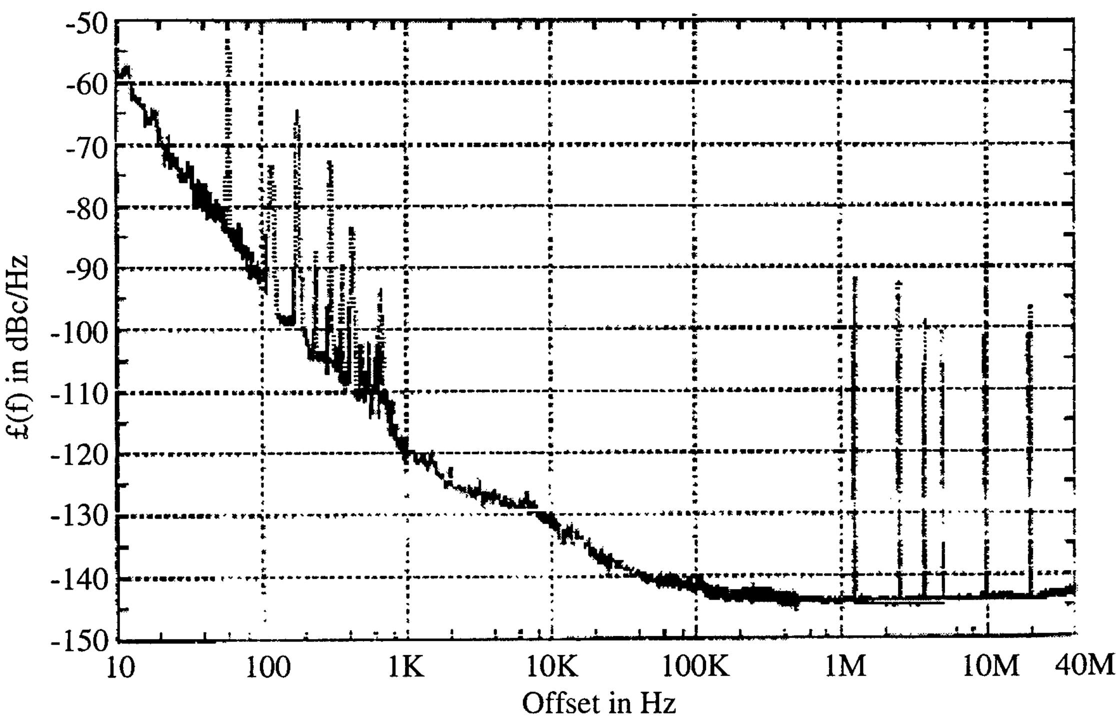

Fig. 7 - SSB phase noise at 8320 MHz

The cluster of spurs in the 60 - 600 Hz region, a typical feature of any phase-noise plot, is due to power-line harmonics. However, the spurs above 1 MHz are not typical features, and they are solely from the DUT. Many of these spurs were also present in the phase-noise plots of the other output frequencies. For instance, the 160 MHz phase-noise plot (not shown) had spurs at the

following offsets: 0.625, 1.25, 2.5, 5.0 and 10.0 MHz. All the spurs in this series originate from the 80 MHz crystal oscillator as it is digitally divided down to yield the various output frequencies. The internal 625 kHz loop error-signal listed in the spur series is also generated from these divisions. Several of these spurs were present in the plots of the 20 and 32.5 MHz outputs as well, thus confirming the presence of cross talk between the various divider circuits within the Wenzel assembly. The 320 MHz SAW filter with its 12 dB of stopband rejection, offered little in the way of suppression of these spurs. However, whether present in the 8320 MHz or the 10 MHz output, these spurs were not troublesome to our application.

The 320 MHz phase-noise plot demonstrates the efficacy of the SAW filter in restoring the noise floor as mentioned in Section 4. The phase noise plot for the 320 MHz output is shown in Figure 8. The relative contribution of each source, as mentioned in the previous paragraph, also applies here. Figure 8 shows the floor of the 320 MHz at -174 dBc/Hz. Allowing for equal contributions to the floor from the two sources would place the 320 MHz floor at -177 dBc/Hz. This floor is the same as the 80 MHz floor given in Table 3. Clearly, the SAW filter, FL3, has restored the floor as predicted. Even though not all visible, the same spurs in the 1.25 to 20 MHz range of the 8320 MHz are also present in the 320 MHz plot. Some of the spurs are on the edge of triggering the spur-plotting routine in the HP 3047 and would be displayed as such had additional runs been made.

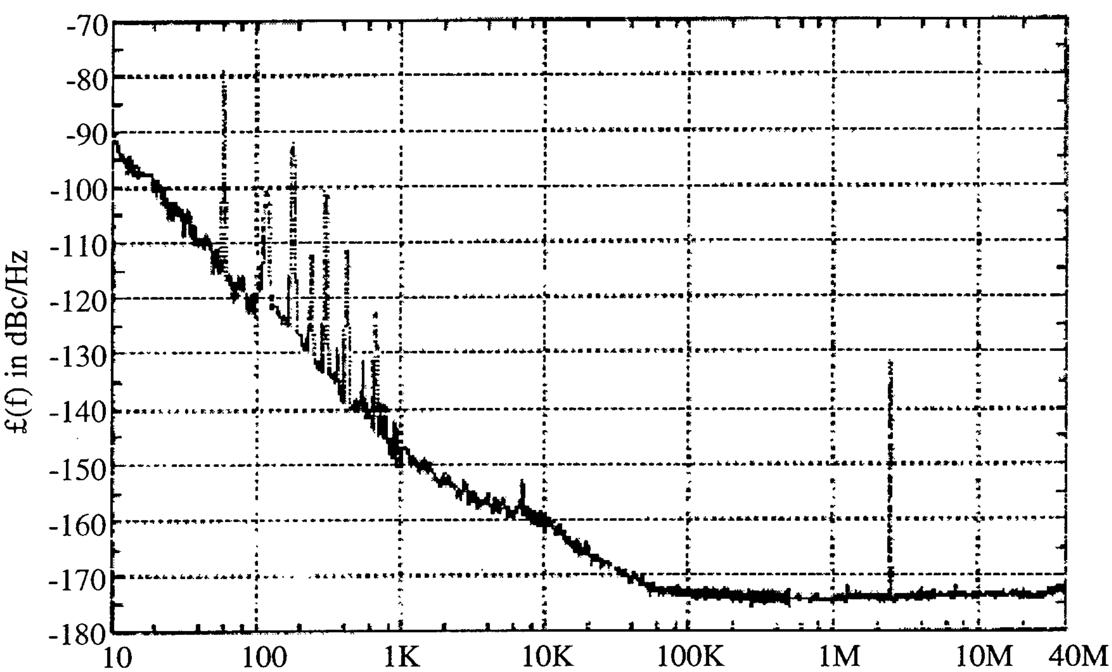

Fig. 8 - SSB Phase Noise at 320 MHz

Table 6 compares the specifications and phase-noise performance of the multi-frequency source to a high-performance, COTS source. The specifications and performance data for the Hewlett Packard HP 71708A microwave source were taken directly from the catalog [2]. The first section of the table lists the salient physical features of each source; while, the second section lists the phase-noise profiles. The phase noise profile for the multi-frequency source was lowered by 3 dB for offsets greater then 100 Hz as discussed above. Clearly, the multi-frequency source offers nearly the same phase-noise performance as the commercial source but at a fraction of the cost.

Moreover, the multi-frequency source is significantly lighter and smaller than its commercial counterpart. Also, the multi-frequency source can provide all the frequencies necessary for a complete radar system.

Table 6 - The Multi-Frequency Source Versus a Commercial Source

Device:	Multi-frequency source	HP 71708A microwave source
Cost:	$19 K (1996)	$63 K (1997)
Weight:	28 lbs.	59 lbs.
HxWxL:	5.25 in. x 17.23 in. x 19.25 in.	8.74 in. x 16.75 in. x 20.70 in.
Output frequencies:	9	1
Tunable band:	0.64 - 16.00 GHz	2.4 - 25.8 GHz
Tuning step size:	640 MHz	600 MHz
SSB phase noise:		
Offset	Measured @ 8320 MHz	Typical @ (7.8 - 10.2 GHz)
(Hz)	(dBc/Hz)	(dBc/Hz)
10	-58	-70
100	-92	-90
1K	-123	-118
10K	-134	-130
100K	-145	-141
Floor	-147	-145

7. DESIGN COMMENTS

Several oversights in the design of the multi-frequency source became apparent after completion of testing and continued use. The first of these was that the 80 MHz was never brought out on a SMA connector like the other outputs of the multi-frequency source.

The non-harmonically related spur specification of -60 dBc across-the-board may be inadequate for some applications. In the future, for each output frequency the required phase-noise profile will have spur levels specified by offset-frequency band and maximum level. The current spurious performance of the Wenzel assembly could be improved by the use of crystal filters on all the outputs; however, this would prevent phase locking of the 80 MHz oscillator as discussed in the following paragraph. Alternatively, the 80 MHz oscillator alone could have been used with external, analog, regenerative dividers instead of the internal digital dividers currently used. The result would be elimination of many of the 80 MHz sub-harmonic spurs in all of the multi-frequency source outputs. The additional circuitry could still fit within the same 19-inch chassis and the considerable savings from purchasing the 80 MHz oscillator alone would offset the associated cost increase. However, the 32.5 and 80 MHz oscillators would still have to be phase locked together for coherency.

The inclusion of a tuning port on the Wenzel assembly was not initially considered. The tuning-port voltage allows the 80 MHz oscillator in the Wenzel assembly to be phase locked to an external reference. Thus, the multi-frequency source can function as the closed-loop reference source with the Hewlett Packard HP 3048 phase-noise test set. Fortunately, Wenzel Associates included a tuning port compatible with the test set and Table 6 lists the tuning-port specifications. In order to prevent stray pickup from phase modulating the 80 MHz oscillator, the tuning voltage will be brought into the Wenzel assembly on coaxial cable.

Table 7 - Tuning Port Parameters for the Wenzel Assembly P/N 500-05125	
Bandwidth:	DC - 500 Hz
Voltage swing:	± 5 V max.
Center voltage:	0 VDC
Frequency deviation:	± 320 Hz
Tuning constant:	64 Hz/V
Tuning linearity:	Linear within 15% of voltage swing
Input resistance:	32K Ω min.

8. CONCLUSION

This report describes a compact, lightweight, ultra-stable source that coherently generates all of the required LO frequencies of a high-performance X-band radar system. This multi-frequency source, has phase-noise performance comparable to a premium.commercial source but is better in terms of cost, weight, and size. Furthermore, the source provides nine output frequencies suitable for a complete radar system. However, unlike a synthesizer, the source cannot be conveniently tuned to an arbitrary frequency. While the X-band phase noise of the source is outstanding, spurs are present beyond offsets of 1MHz. Several design improvements were discussed to reduce these spurs and to make use of the tuning port for external phase locking.

9. ACKNOWLEDGMENT

The authors wish to express their gratitude to Mike Driscoll of NGC for providing his designs of the multi-frequency source and the 320 MHz SAW filter. The Defense Sciences Office of the Defense Advanced Research Project Agency (DARPA) provided funding for construction of the multi-frequency source.

10. REFERENCES

1. J.A. Scheer and J.L. Kurtz, *Coherent Radar Performance Estimation*, Artech House, Norwood MA, 1993.

2. Hewlett Packard Company, *Modular Measurement System Catalog*, July 1993.

APPENDIX: PARTS LIST FOR THE MULTI-FREQUENCY SOURCE

COMPONENT	VENDOR	MODEL	QTY	COST ($)
Wenzel assembly	Wenzel Associates	500-05125	1	6675
SAW resonator	Sawtek	851779	2	815
SAW packaging	Tele Tech	N/A	2	1567
amplifier	Penstock	UTC-518-1	4	796
	Penstock	UTC-1023-1	1	273
	Penstock	UTC-2023-1	2	908
	Penstock	DFT-12662	1	825
	Q-Bit	QBH-9-138	1	188
	Q-Bit	QBH-9-145	1	197
	Q-Bit	QBH-9-176	1	207
step recovery diode	Herotek	GC640NC	1	476
frequency doubler	Watkins-Johnson	WJ-FD25HC	4	848
mixer	M/A-Com	MDC-174	2	600
power divider	Merrimac	PDM-20-500	1	155
coupler	Merrimac	CSM-10M-.75G	1	175
coupler	Merrimac	CRM-10-500	2	400
filter	Lorch Microwave	4BP8-160/16-S	2	380
		4BP8-150/10-S	1	190
		4BP8-320/32-S	1	190
		4BP8-640/64-S	2	380
		4BP8-1280/128-S	1	190
		6CFX-1430/10-S	2	950
		6EZ6-8320/250-S	1	450
power supply	Lambda	LDS-X-15	1	545
chassis	Techmar	SRK-7H-24D-FBP	1	425

Total cost (FY 96 dollars): $ 18,805